Virtual fracture reduction of the acetabulum using a rigid body biomechanical model

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Introduction

Acetabular fractures are a challenge in orthopedic surgery. Many fracture patterns occur [1], in a deep anatomical area surrounded by numerous vascular and nervous elements, generally in a polytraumatic context. A reduction with less than 2mm of incongruence is generally considered acceptable [2], to limit the post-operative osteoarthritis that could rapidly require total hip arthroplasty. Due to the long learning curve, this surgery is limited to large reference centers [3].
A full understanding of the fracture, based on CT images and 3D reconstructions, is required to specify the best planning, especially the surgical acces(es). Several preoperative planning tools have been proposed [4-6]. The different bone fragments are first segmented in the CT images, then mobilized in 3D to simulate the fracture reduction. This result can then be used to conform osteosynthesis plates to the patient anatomy, and define the number and length of fixation screws. These authors have reported a much better understanding and definition of the surgical strategy, which lead to a significant reduction of the per-operative duration. However, several key challenges remain to use such systems in clinical routine. After presenting our current strategy for the segmentation, the main contribution of this paper is an intuitive simulation of the fracture reduction using a mechanical model.

Material & Methods

A 3D model of the hip bones, including separated fragments, is first build out of the CT images. Semi-automatic segmentation procedures are usually performed using commercial software likes Mimics® or Amira® [4,5] or via the development of advanced methods to increase the automation of the process [7,8], which currently remains too time-consuming for a clinical routine use. In this study, we have used an existing non-commercial software (itksnap [9]), to perform automatic threshold, region growing with active contours and finally manual refinements. Models of adequate quality (figure 1), similar to other authors, could be built in less than 30 minutes in complex cases.
The next crucial step is the simulation of the fracture reduction. All authors in the literature propose geometrical repositioning of each bone fragment, with six degrees of freedom (translation + rotation). However, reducing the fracture in 3D through mouse interactions is difficult, quite non-intuitive and hardly guaranty non-penetration between fragments. [6] have thus proposed a virtual environment controlled with a haptic device reacting to collisions. One of the main drawback of all these methods is that their goal is simply to position the bone fragments so that the fracture is considered as reduced. However, even if this target position is *in fine* correct, the process to achieve does not correspond to the reality of the surgical procedure: fragments are moved freely

in 3D space, with few or no anatomical consideration, resulting to movements that may not be realized in real surgery.
A new paradigm is then to *simulate the procedure itself*, instead of the desired result. During surgery, bone fragments are repositioned using clamps, hooks or Schanz screws (figure 2). The fracture is then reduced via the application of *forces* by the physician. Moreover, the surgeon use the contacts between structures, e.g. lean the ischium on the femoral head, to produce the expected movements. To simulate such a procedure we have chosen to use a mechanical model of the hip joint bony elements, implemented within the non-commercial Artisynth framework [10]. Each bone fragment is considered as an independent rigid body. One of them is usually considered as fixed, e.g. the anterior or posterior column and/or the femoral head. Collisions are handled to ensure non-penetration between elements, with dry friction (Coulomb) response. The action of a clamp is simulated via a Hill muscle model which extremities are the clamp jaws positions on the bones. The interactive "contraction" of this model apply forces similarly to the real clamp action. In reality, the muscular system apply heavy constraints to the bones during their repositioning. While modeling this accurately is an extremely complex problem, moreover in a patient-specific context, a first approximation is to add a strong global damping to the all system. Even if preferred anatomical directions are not accounted for, this high resistance ensure the response to collisions and numerical instabilities are very low in comparison to the forces directly applied to the bones. When all these elements are set, the dynamic numerical system is solved using traditional methods (Euler implicit, Runge-Kutta…).

Results

Figure 2 present a clinical case with a "simple" transverse + posterior wall fracture of the acetabulum. The position of the clamps is chosen by the surgeon according to his knowledge of the surgical approach and the feasibility of the procedure. A fracture is the result of a non physiological displacement in a contraignant soft tissue area. The surgeon tries to reproduce, in the other way, the initial displacement to get a perfect reduction. The best reduction is obtained when the less of manipulations are made. We have simulated several ways of reduction and the best procedure is presented here. Each procedure tested was technically feasible in real surgery (the position of the clamps, the direction of the displacements, the strength on the bones, the motion of the bones).Two clamps are successively used, to close the gap between the ischium and ilium then to slide the ischium in its final reduced position. The user just has to set the clamps position and to control their activation, the simulation being run in real-time. The simulation is quite stable, and the moved fragments are clearly sliding over the fixed ones along with the clamp closing, according to the behavior expected during surgery. The final simulated reduction is qualitatively correct.

Conclusion

A new method has been proposed for virtual fracture reduction. Unlike unconstrained geometrical repositioning, the biomechanical model enables to easily and intuitively simulate the effects of real surgical procedures. Even if limits could be addressed, especially the soft tissue environment of the hip area, preliminary results are quite promising. This technique could be an effective planning tool for the surgeon to define his best therapeutic strategy, mostly which surgical access to choose as well as how and in which order to reposition the bone fragments.

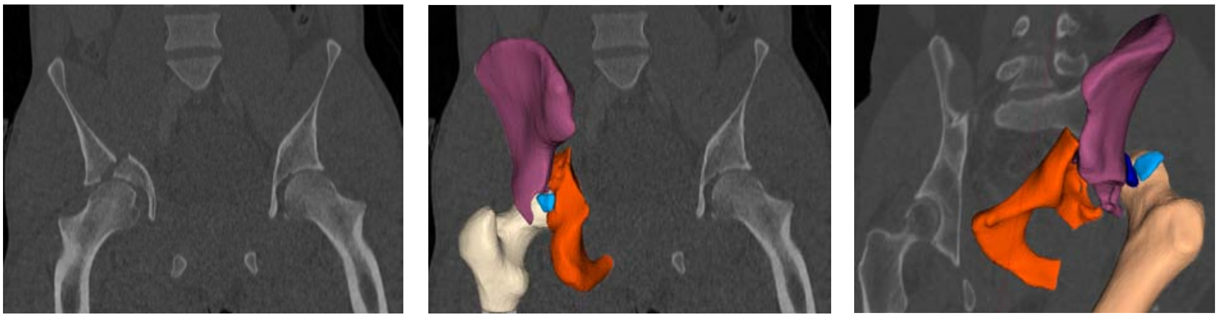

Figure 1 Example of transverse + posterior wall fracture of the acetabulum (left: CT image only; middle: along with the reconstructed 3D model). Right: a more complex case with two comminutive fragments and a dislocation of the femoral head.

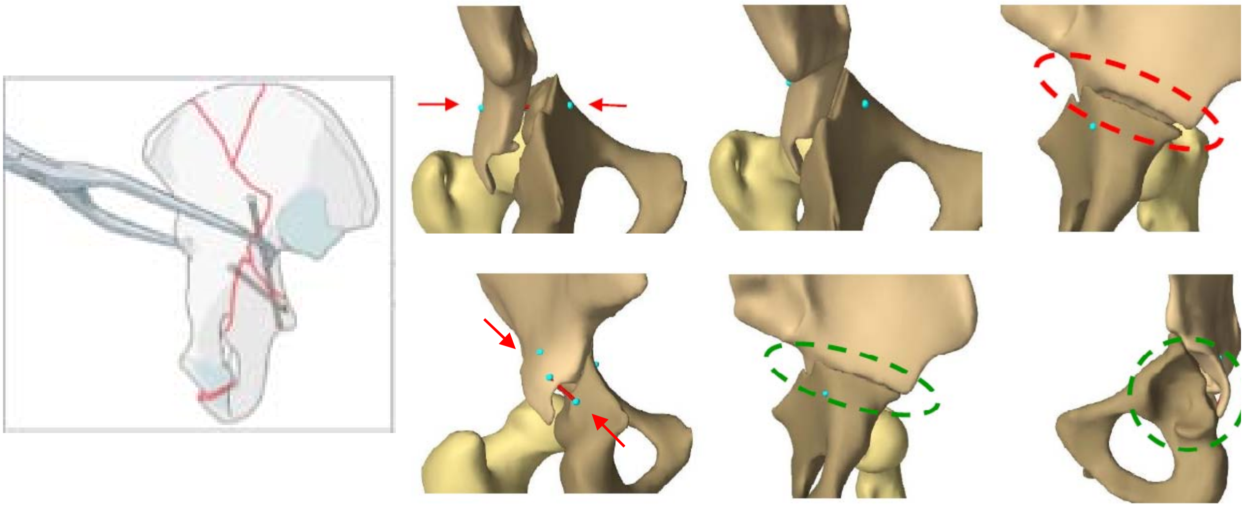

Figure 2 Left: examples of clamps and screws used to reduce a fracture. Top row: simulation of the first clamp action. Second raw: simulation of the second clamp. The fracture is finally reduced (a comminutive fragment is not display here).

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